

# Design and Development of an Intake Manifold System for A Formula Student Vehicle

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**ABSTRACT**– This study presents a system-level intake design methodology for a single cylinder motorsport engine, developed with the objective of improving midrange performance under packaging and regulatory constraints. A representative engine operating speed was identified using lap time simulation, and this operating point served as the basis for subsequent intake system design. The intake restrictor was designed and evaluated using computational fluid dynamics and experimental flow characterization to assess pressure recovery behavior. Intake runner length was selected using one-dimensional acoustic wave theory, while the plenum geometry and volume were determined based on literature guidelines and total intake system volume constraints. The complete intake system was modeled as a complex component in a one-dimensional engine simulation framework using Ricardo WAVE and evaluated over an engine speed range of 2500–11000 rpm. Simulation results were analyzed in terms of brake torque and brake power trends and were compared qualitatively with vehicle chassis dynamometer data. The results demonstrate consistent mid-range performance trends between numerical predictions and experimental observations, indicating that the adopted multi-fidelity design approach is suitable for intake system development in regulated motorsport applications.

**KEY WORDS:** Intake system, Restrictor, Formula Student, Acoustic tuning, CFD, 1D engine simulation

## NOMENCLATURE

RV : Reflective Value

L= volume, litre

## 1. INTRODUCTION

Restricted intake systems are widely employed in small-displacement single cylinder engines used in motorsport and prototype vehicle applications. A prominent example is the Formula Student (FS) competition, where intake restrictors are mandated to limit engine power and ensure parity among competing vehicles (Formula Bharat, 2024; SAE Supra, 2024). Under such constraints, the intake system becomes a dominant factor governing engine breathing, as pressure losses introduced by the restrictor directly limit the achievable mass flow rate and consequently engine performance (Heywood, 1988). In FS and similar applications, engines typically operate over a narrow speed range dictated by vehicle dynamics, track layout, and gear ratios. As a result, intake system design must be targeted toward a representative operating engine speed rather than peak power conditions. The intake system must therefore be carefully designed to minimize restrictor-induced losses, promote pressure recovery within the plenum, and exploit acoustic wave dynamics in the intake runner to enhance cylinder filling near the most relevant operating point (Payri et al., 2010). Despite its importance, intake system design for restricted single-cylinder engines is often guided by empirical rules or isolated numerical studies, with limited experimental validation. Many existing investigations rely solely on computational fluid dynamics (CFD) or one-dimensional (1D) engine simulations, frequently employing assumed boundary conditions that are not directly linked to experimentally measured flow characteristics. This disconnect can introduce uncertainty in predicted trends and

reduce confidence in the resulting design decisions. An effective intake system for a restricted FS engine must simultaneously address multiple interacting phenomena, including pressure losses across the restrictor, pressure recovery in the plenum, unsteady acoustic effects in the intake runner, and system-level engine behavior. Achieving this balance requires an integrated methodology that combines experimental measurements with multi-fidelity numerical tools while maintaining consistency across different modeling approaches. The present work presents a validated intake system design methodology for a restricted single-cylinder engine representative of a Formula Student application. The approach integrates CFD simulations, acoustic wave theory, and 1D engine simulations to systematically develop and evaluate the intake system. Experimental measurements are used to define numerical boundary conditions, allowing a direct comparison between simulations and physical tests. Vehicle-level considerations are incorporated to identify the representative engine's operating speed, ensuring on-track relevance. The objective of this study is to demonstrate a transparent and reproducible intake system design framework applicable to restricted single cylinder engines operating under similar constraints.

## 2. IDENTIFICATION OF REPRESENTATIVE ENGINE OPERATING SPEED

The intake system was designed to improve engine breathing near the operating conditions most relevant to on-track vehicle performance. In Formula Student applications, engine operation is governed not by peak power conditions but by vehicle dynamics, gear ratios, and track layout. Consequently, identifying a representative engine's operating speed is a critical prerequisite for intake system design. To determine the dominant engine speed range, a lap time simulation was

performed using Optimum Lap. A baseline engine torque map was used in the simulation to avoid biasing the results toward any specific intake configuration. All vehicle parameters, including mass, gear ratios, tire properties, and aerodynamic characteristics, were kept constant throughout the analysis. The simulation was conducted on a representative Formula Student autocross-style track layout. The primary output of interest from the lap simulation was the distribution of engine operating speed over the lap, shows the percentage of lap time spent at different engine speeds. The results indicate that the engine operates predominantly in the range of 6000–7000 rpm, with the highest time fraction centered around approximately 6500 rpm. This operating range corresponds primarily to acceleration zones and corner exits, where engine torque has a direct influence on vehicle performance. Based on this analysis, an engine speed of 6500 rpm was selected as the representative design point for the intake system. The intake runner length and plenum volume were subsequently designed using acoustic wave theory and pressure fluctuation considerations to enhance cylinder filling and pressure recovery near this operating condition. The lap simulation was used solely to identify the representative engine speed range and not to predict absolute lap times (Payri et al., 2010).



TRANSMISSION DATA	
Transmission Type Sequential Gearbox	
Add / Remove Gears	
	Gear Ratios
► Gear 1	2.6600
Gear 2	1.8500
Gear 3	1.4200
Gear 4	1.1420
Gear 5	1.0450
Gear 6	0.8400

Figure 1. Input transmission data for Optimum Lap.



General Data	
Vehicle Type FSAE	
Mass 340.000 kg	Driven Type 2WD
Aero Data	
Drag-Lift	Efficiency-Lift
Drag Coefficient 0.600	Downforce Coefficient -0.010
Front Area 1.300 m <sup>2</sup>	Air Density 1.230 kg/m <sup>3</sup>
Tire Data	
Tire Radius 0.330 m	Rolling Resistance 0.030
Longitudinal Friction 1.400	Lateral Friction 1.500

Figure 2. Input General vehicle data for Optimum Lap.

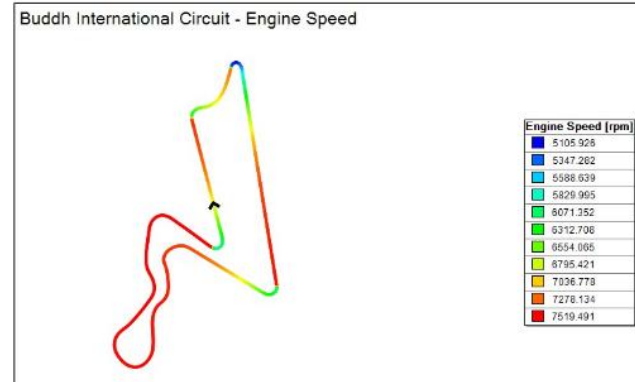


Figure 3. Optimum lap simulations, showing the car's run and engine speed at Buddh International Circuit.

### 3. RESTRICTOR DESIGN AND EXPERIMENTAL– NUMERICAL METHODOLOGY

In Formula Student applications, the intake restrictor represents the primary flow-limiting element of the intake system and therefore has a dominant influence on engine breathing characteristics. Pressure losses introduced at the restrictor directly limit the mass flow rate available to the engine, making restrictor design and validation a critical step in the overall intake system development. The restrictor's diffuser length was constrained by the available packaging space within the vehicle. While longer diffusers are generally favorable for pressure recovery, practical limitations imposed an upper bound on the diffuser length (White, 2006; Kataoka and Sugiyama, 2004). A diffuser length of 100 mm was therefore selected as a compromise between performance and packaging feasibility. The subsequent numerical analysis focuses on evaluating whether this configuration provides acceptable pressure recovery characteristics rather than achieving a globally optimal geometry.

#### 3.1. Restrictor Geometry and Design Objective

The restrictor geometry was designed in accordance with Formula Student regulations, which impose a maximum throat diameter to limit engine power. The primary design objective was to minimize total pressure losses across the restrictor while maintaining stable flow characteristics over the operating 5 mass flow range relevant to the target engine speed (Kataoka and Sugiyama, 2004). Attention was given to the inlet contraction profile and diffuser angle to reduce flow separation and promote pressure recovery downstream of the throat.

### 3.2. Numerical Methodology

Three-dimensional CFD simulations were performed to evaluate the flow behavior through the restrictor. The simulations focused on predicting pressure loss, velocity distribution, and potential regions of flow separation. A steady-state approach was adopted, as the restrictor operates under quasisteady conditions relative to the unsteady behavior of the downstream intake components. The computational domain included the upstream inlet section, the restrictor throat, and a downstream diffuser section extending into the plenum interface. A structured or hybrid mesh with local refinement was used in regions of high velocity gradients, particularly near the throat and diffuser walls. Grid independence was assessed to ensure that the predicted pressure losses were not sensitive to mesh resolution.

Table 1. Summary of numerical setup parameters used in the CFD simulations

Turbulence model	k-ε SST
Working fluid	Air (ideal gas)
Total cell count	410,235
Inlet boundary condition	Mass flow rate (experimentally derived) = 0.02kg/sec
Outlet boundary condition	Static pressure = 101.32 KPa

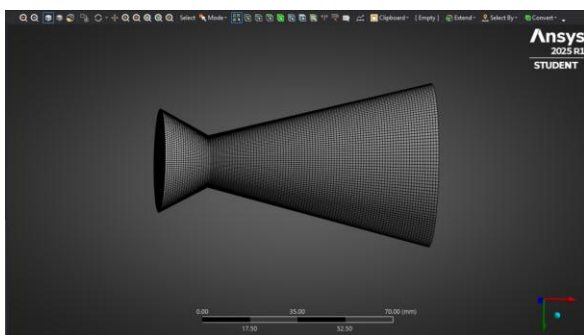


Figure 4. Computational mesh used for the restrictor simulations, showing local refinement near the throat and diffuser regions.

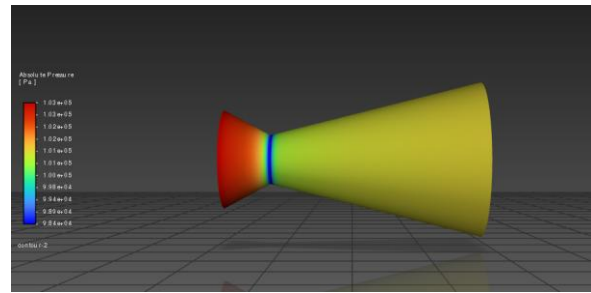


Figure 5. CFD result showing absolute pressure contour

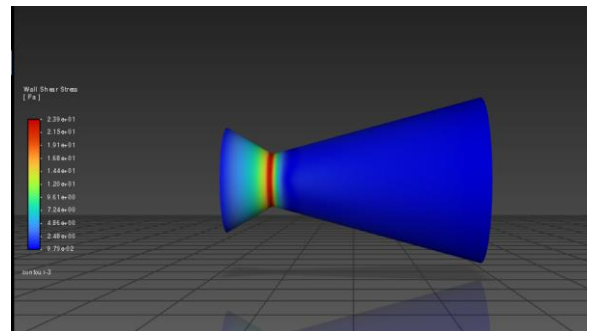


Figure 6. CFD result showing wall shear stress

### 3.3. Boundary Conditions Based on Experimental Setup

To reduce uncertainty associated with assumed numerical boundary conditions, the CFD inlet conditions were derived from the experimental test configuration. The inlet mass flow rate and corresponding velocity levels were defined based on measurements obtained from the test setup, ensuring consistency between numerical and experimental conditions. The outlet boundary was specified using a static pressure condition representative of the downstream plenum environment. Previous studies have shown that diffuser effectiveness improves with increasing length up to a point, beyond which gains diminish under space-constrained conditions. Within the imposed packaging limits, the selected diffuser length demonstrates stable flow behavior and satisfactory pressure recovery, as evidenced by the absence of large-scale separation in the CFD results.



Figure 7. The test setup for Experimental characterization of restrictor

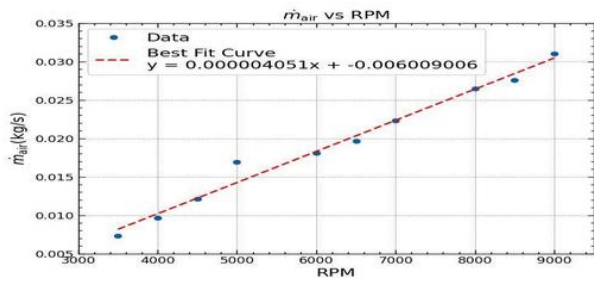


Figure 7. The measured mass flow rate as a function of engine speed.

### 3.4. Pressure Recovery Assessment

The primary performance metric for the restrictor was the static pressure recovery downstream of the throat. The objective was not to achieve complete recovery to atmospheric pressure, which is theoretically unattainable due to irreversible losses, but rather to maximize pressure recovery as closely as possible within the imposed geometric constraints. The spatial distribution of static pressure along the restrictor axis was therefore analyzed to identify loss mechanisms and evaluate diffuser effectiveness.

## 4. INTAKE RUNNER LENGTH SELECTION USING ACOUSTIC THEORY

The intake runner length was determined using one-dimensional acoustic wave theory, which relates pressure wave propagation to intake valve timing and engine speed. In a four-stroke single-cylinder engine, the intake valve opens once every two crankshaft revolutions, generating unsteady pressure waves that propagate along the intake runner and reflect at geometric discontinuities such as the plenum interface. Proper selection of runner length allows reflected pressure waves to arrive at the intake valve during a favorable phase of the intake event, thereby enhancing cylinder filling. The representative engine operating speed was identified as 6500 rpm based on lap time simulation, as discussed in Section 2. At this speed, the intake event duration was calculated from the engine rotational speed, and the corresponding wave travel time was evaluated assuming a speed of sound of 343 m/s at ambient conditions. The runner length was estimated using the concept of a reflective value (RV), which represents the number of pressure wave traversals between the intake valve and the plenum interface within a single intake event. Higher reflective values correspond to higher-order acoustic reflections and result in shorter, physically realizable runner lengths suitable for space-constrained applications (Heywood, 1988; Winterbone and Pearson, 1999). Table 2 summarizes the calculated runner lengths for a range of engine speeds and reflective values. At 6500 rpm, a single wave traversal yields a theoretical runner length of approximately 2313 mm, which is not feasible within the available packaging space.

Increasing the reflective value reduces the effective runner length. For a reflective value of  $RV = 12$ , the calculated runner length at 6500 rpm is approximately 193 mm. Based on these calculations, a runner length of approximately 190 mm was selected for the intake system. This length represents a compromise between acoustic tuning effectiveness and packaging constraints, targeting improved cylinder filling near the dominant operating speed rather than peak power conditions. The selected runner geometry was subsequently evaluated as part of the complete intake system using one-dimensional engine simulation, as discussed in a later section.

Table 2. Intake runner length estimation based on acoustic wave travel time for different engine speeds and reflective values

Engine speed (RPM)	Inlet valve open time	Runner length RV = 4 (mm)	Runner Length RV = 12 (mm)
5000	0.0087	751.7	250.6
5500	0.00797	455.6	227.8
6000	0.00731	417.6	208.8
6500	0.00674	385.5	192.8
7000	0.00626	358.0	179.0
7500	0.00584	334.1	167.1
8000	0.00548	313.2	156.6

## 5. PLENUM VOLUME SELECTION AND GEOMETRIC CONSIDERATIONS

The intake plenum functions as a pressure reservoir that decouples the highly unsteady flow within the intake runner from the upstream restrictor. Its primary role is to attenuate pressure fluctuations arising from intermittent intake valve events and to provide a relatively uniform pressure boundary condition at the runner inlet (Payri et al., 2010). This function is particularly important in single-cylinder engines, where intake pulsations are more pronounced compared to multi-cylinder configurations. In the present work, the plenum geometry was designed using smooth Bezier curves to ensure gradual area variation between the restrictor outlet and the runner inlet. The use of Bezier-based profiles avoids sharp geometric discontinuities, which are known to promote flow separation and localized pressure losses. The smooth curvature of the plenum walls was therefore selected to facilitate uniform flow distribution and to support pressure recovery downstream of the restrictor. The plenum volume was selected based on a combination of empirical intake design guidelines, literature recommendations, and overall intake system volume constraints. Previous studies on naturally aspirated intake systems indicate that the total intake system volume, including the plenum and runner, should typically lie within a limited multiple of the engine displacement to balance pressure stability, throttle response, and packaging feasibility. Based on a survey of existing intake design literature, a target total intake volume of

approximately 2.8 L was identified as a reasonable upper bound for the present application. Given the selected runner length discussed in Section 4, the plenum volume was consequently limited to approximately 2 L to maintain the overall intake system volume within the targeted range. This volume was deemed sufficient to damp pressure oscillations generated during intake valve opening events, while avoiding excessive volume that would offer diminishing performance benefits and impose additional packaging penalties. The selected plenum volume was not intended to act as a primary acoustic tuning element through Helmholtz resonance. Instead, it was designed to function as a pressure stabilization chamber that complements the acoustically tuned intake runner. The interaction between the plenum, runner, and restrictor was subsequently evaluated using one-dimensional engine simulation to assess mass flow rate consistency and pressure recovery behavior under representative operating conditions.

## 6. ONE-DIMENSIONAL ENGINE SIMULATION AND SYSTEM-LEVEL EVALUATION

To evaluate the combined effect of the restrictor, intake runner, and plenum on overall engine performance, a one-dimensional engine simulation was carried out using Ricardo WAVE. The purpose of the simulation was not to predict absolute performance metrics with high fidelity, but to assess relative trends and to verify that the designed intake system supports the targeted engine operating range identified earlier (Merker et al., 2012). The complete intake geometry, including the restrictor, plenum, and intake runner, was modeled in Ricardo WAVE (Ricardo Software, 2022) using a complex component. This approach allows the detailed intake geometry developed in the three-dimensional design stage to be incorporated into the one-dimensional simulation framework while retaining its flow and volume characteristics. The remaining engine components, including the cylinder, intake valve, exhaust system, and boundary conditions, were modeled using standard one-dimensional elements available within the software. Combustion was modeled using a spark-ignition Wiebe heat release model, which provides a simplified yet widely accepted representation of combustion phasing and burn duration in naturally aspirated spark-ignition engines. The combustion parameters were selected to represent stable and repeatable combustion behavior and were held constant across the simulated operating range in order to isolate the influence of the intake system on engine performance. The engine model was simulated over a speed range from 2500 to 11000 rpm, covering low-speed operation, the dominant mid-range identified from lap simulation, and the upper speed limit of engine operation. For each operating point, steady-state simulations were performed, and the resulting brake torque and brake power were extracted for analysis. The simulation results are presented in terms of brake torque and brake power as functions of engine speed. Particular attention is given to the mid-range engine speeds around 6500 rpm, where the intake runner and plenum were acoustically and volumetrically tuned. The trends observed in the simulated results provide insight into the effectiveness of the intake system design in supporting improved cylinder filling and pressure recovery near the representative operating

conditions. It is emphasized that the one-dimensional simulation was used as a comparative and validation tool rather than a definitive predictor of absolute engine performance. The results are intended to demonstrate consistency between the design objectives established during the intake development process and the system-level engine response.

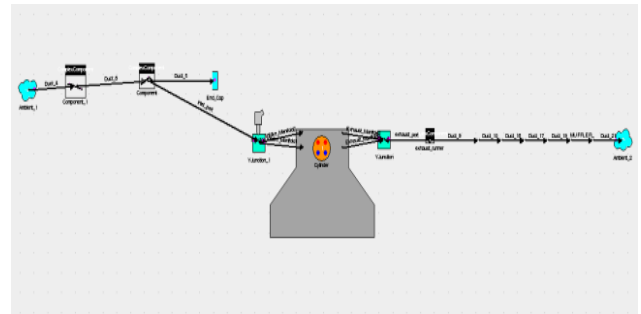


Figure 7. One-dimensional engine model developed in Ricardo WAVE.

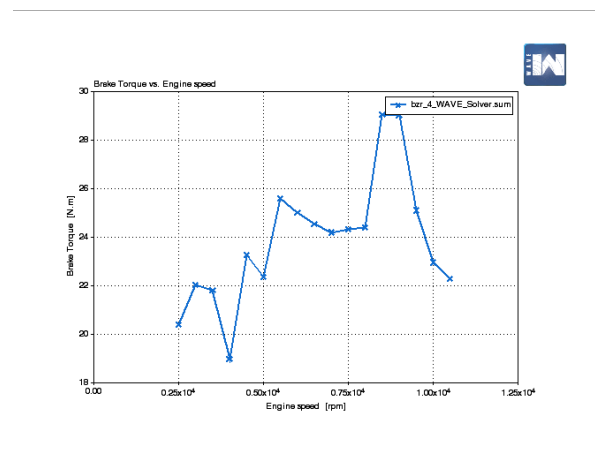


Figure 8. One-dimensional engine simulation results showing brake torque vs RPM

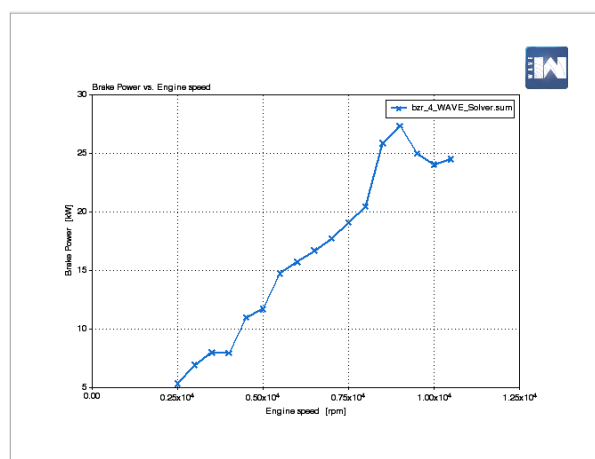


Figure 9. One-dimensional engine simulation results showing Brake Power vs RPM

### 6.1. Comparison with Experimental Dynamometer Data

To evaluate the effect of intake system tuning on engine performance, chassis dynamometer testing was conducted with two configurations: the untuned baseline intake system and the tuned intake system developed in this study. The chassis dynamometer measures torque and power at the driven wheels, thereby capturing overall vehicle performance including drivetrain losses.

Figure 8 presents the wheel torque and wheel power curves obtained from the two dynamometer runs over the operating engine speed range. The untuned configuration represents the baseline system, while the tuned configuration incorporates the intake runner geometry designed using the one-dimensional simulation approach.

The results show that the tuned configuration demonstrates improved performance in the mid-range engine speed region around 6500 rpm, which was selected as the primary design point for the intake system. The increase in wheel torque in this region indicates improved cylinder filling due to intake tuning effects. Overall, the chassis dynamometer results validate that the tuned intake configuration provides a measurable performance benefit compared to the untuned baseline.

## 7. CONCLUSION

This study presented a structured intake system design methodology for a Formula Student single-cylinder engine, integrating vehicle-level operating point identification, aerodynamic analysis, acoustic runner tuning, and one-dimensional engine simulation. The approach emphasizes alignment between intake system characteristics and representative on-track operating conditions. A representative engine speed of 6500 rpm was identified using lap time simulation and served as the primary design target. Based on this operating point, a converging-diverging restrictor, an acoustically tuned intake runner of approximately 190 mm, and a Bezier-based plenum with a volume of approximately 2 L were designed within packaging and regulatory constraints. The intake system was evaluated using computational fluid dynamics and one-dimensional engine simulation, supported by experimental flow characterization and chassis dynamometer data. The results demonstrate consistent mid-range performance

trends across numerical and experimental analyses, indicating that the designed intake system meets the intended design objectives. The methodology presented in this work provides a practical framework for intake system development in regulated motorsport applications, where performance, packaging, and compliance constraints must be addressed simultaneously

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